Synthetic Sky Surveys

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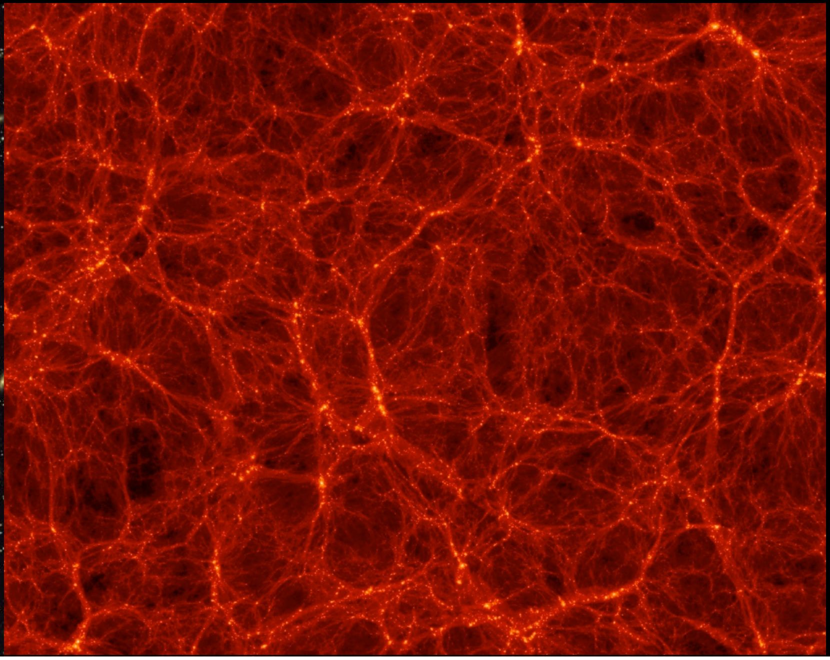


The Dark Energy Survey 2012-2018

- 300 million galaxies
- 1/8 of the sky
- ~ 2.5 magnitudes deeper than SDSS
- g,r,i,z,Y + overlap with VISTA (JHK) + SPT
- first light October 2012

LSST 2019-2029

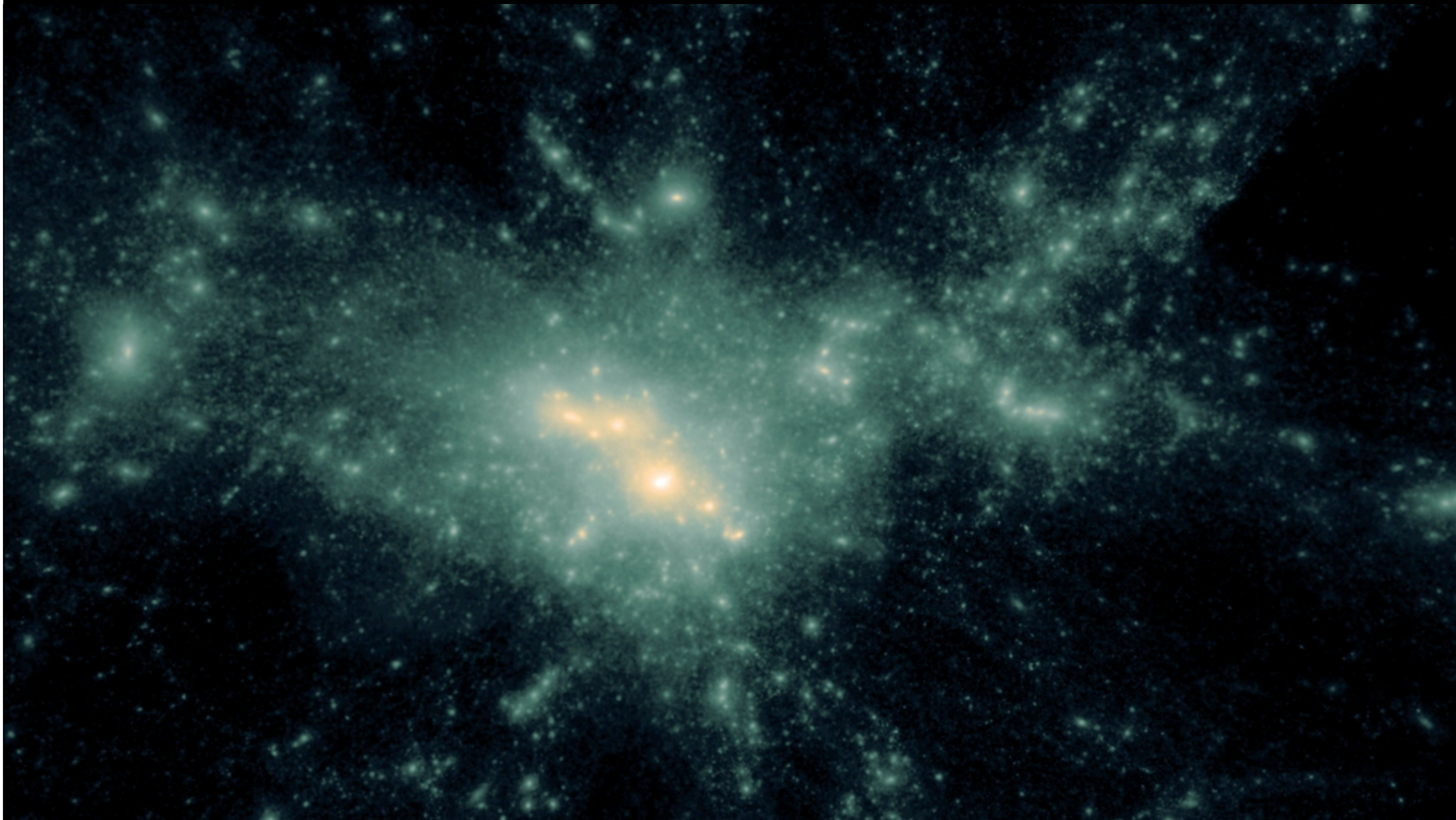
- 10 billion galaxies
- half the sky
- 5 magnitudes deeper than SDSS
- image every 3 nights
- 30 TB/night, ~100 PB over 10 years

- galaxy positions
- magnitudes
- colors
- SEDS
- shapes
- sizes
- morphologies, including substructure within galaxies
- impact of lensing (shear, magnification, multiple images)
- impact of the atmosphere and telescope
- correlations between all of the above
- scales from very small (object detection) to very large (size of surveys; tens of Gpc)

use of simulations in interpreting survey data

★ several goals that require the same sort of simulations, e.g.:

- precise predictions for a variety of structure formation probes
- development and *verification* of science ready codes to work on large volumes
- understanding the instrument
- understanding observational systematics
- covariance matrices to determine error bars. needed not just for one measurement, but for many (e.g.: lensing, galaxy clustering, galaxy clusters)
- impact of galaxy formation & galaxy selection (type dependent bias)



dark matter halos are the basic unit of structure formation and of galaxy formation

resolve
dark matter halos
and substructures
and merger histories
for the galaxies
you want to model
properly.

ways to model galaxies

- hydrodynamical simulations (resolve all histories, with baryonic physics)
- semi-analytic models (resolve all histories)
- empirical connection to dark matter
  - subhalo abundance matching (resolve all subhalos)
  - halo occupation (resolve all host halos)
  - dark matter density based

resolution requirements depend on method.
correlations may depend on method.
what you can infer may depend on the method.

Behroozi et al 2012a,b

rockstar halo finder

Robust Overdensity Calculation using K-Space Topologically Adaptive Refinement

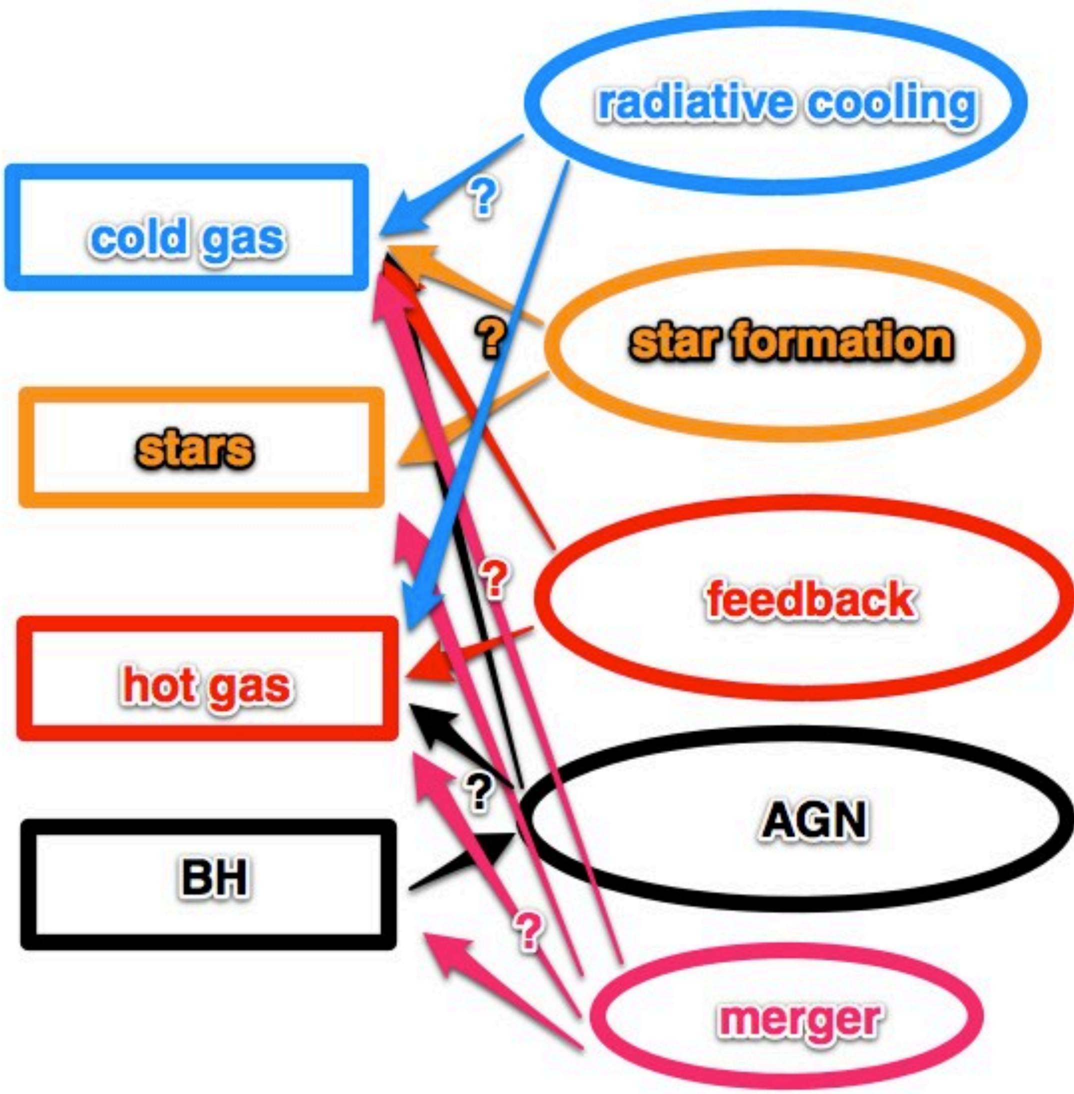
http://code.google.com/p/rockstar

consistent-trees

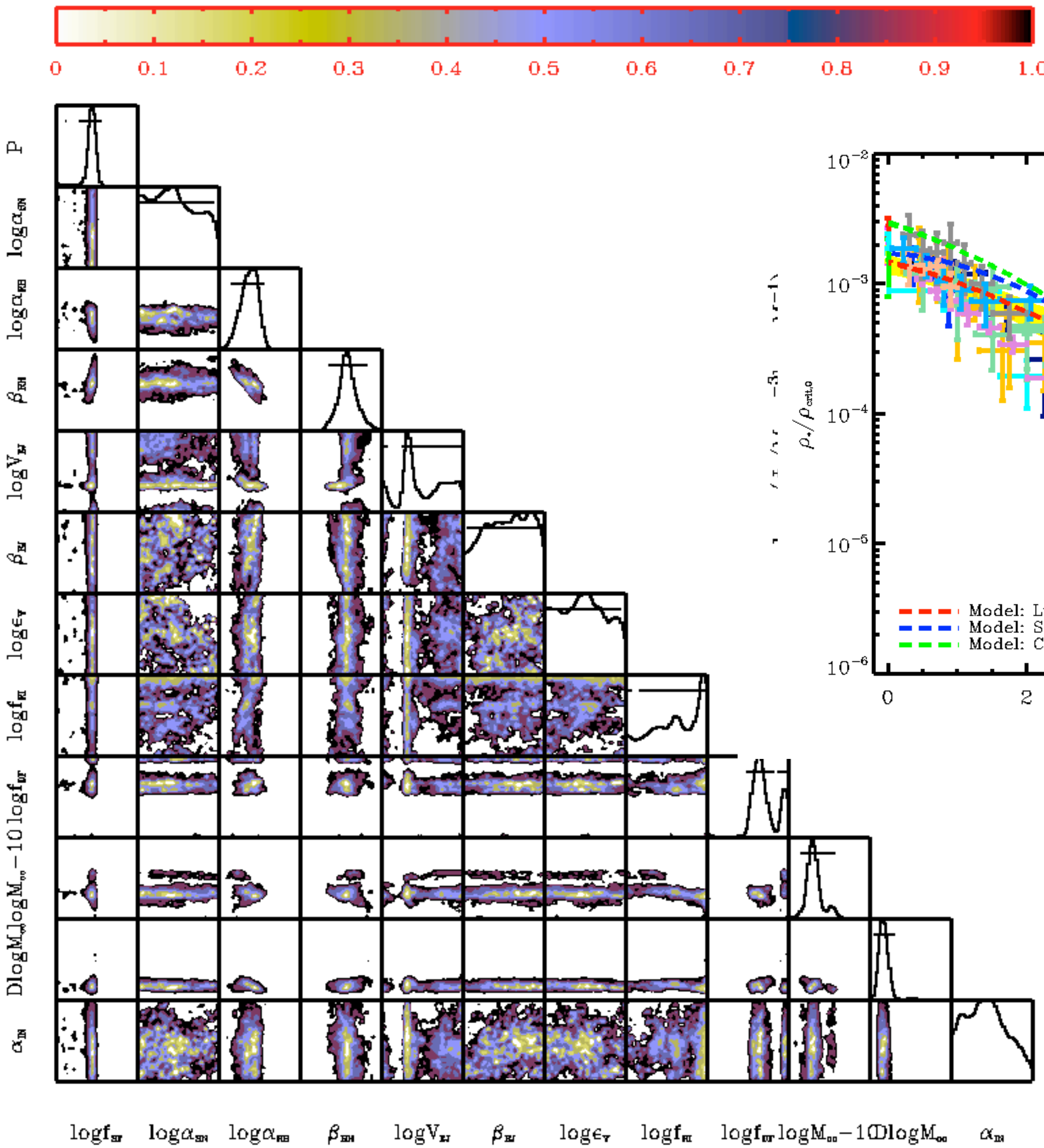
merger tree code that assures gravitational consistency between snapshots

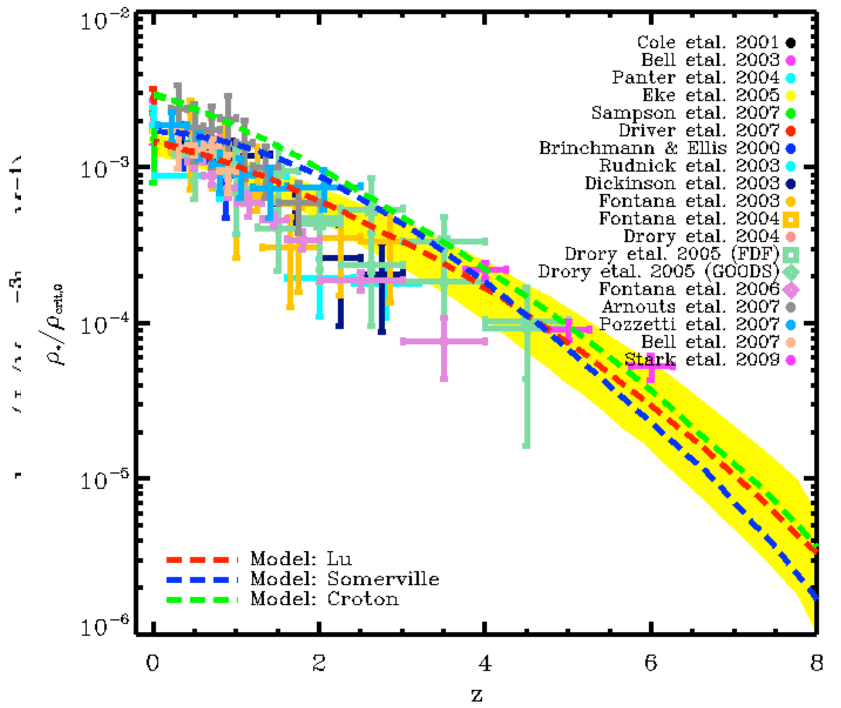
http://code.google.com/p/consistent-trees

galaxy formation



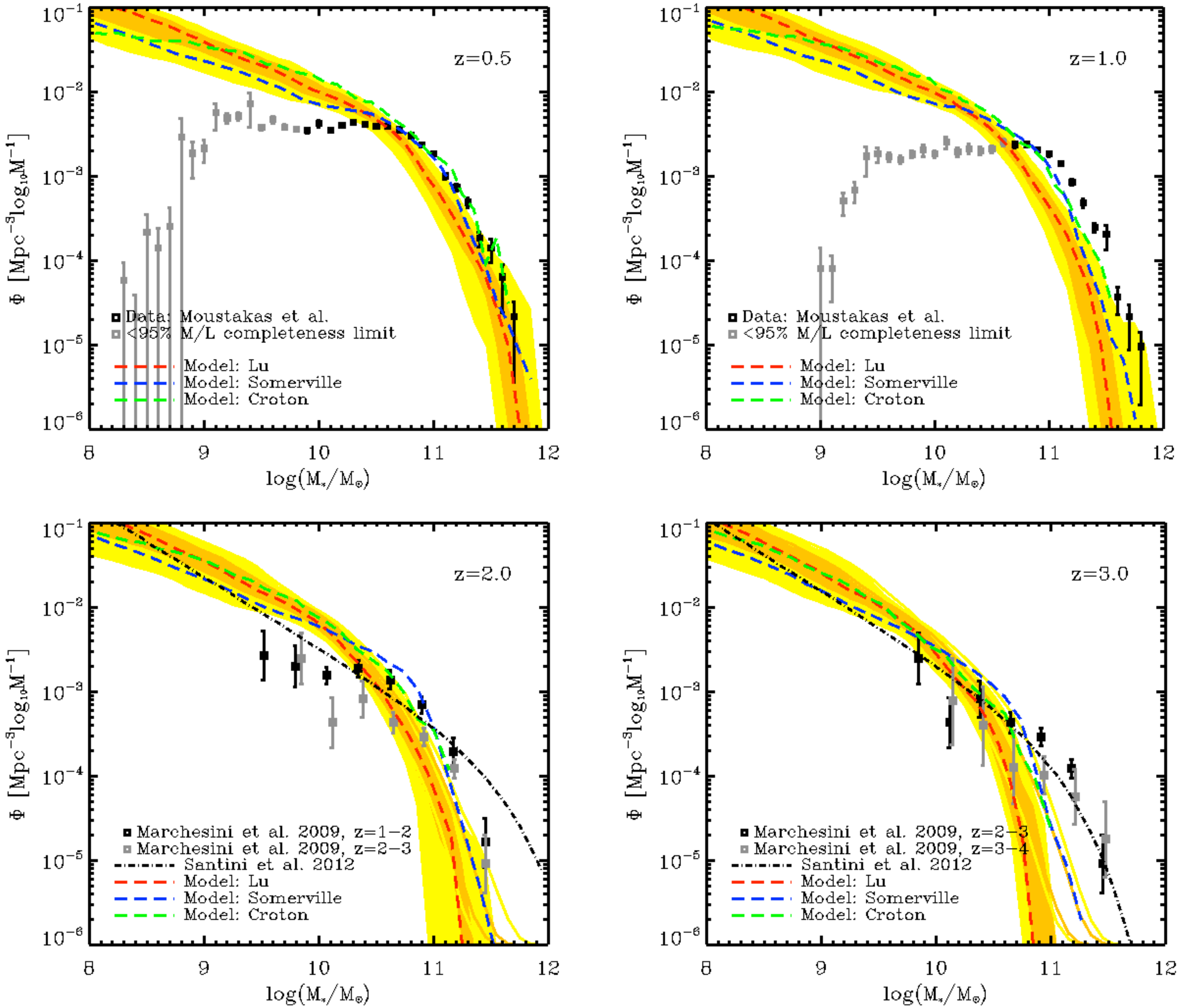
slides from Yu Lu





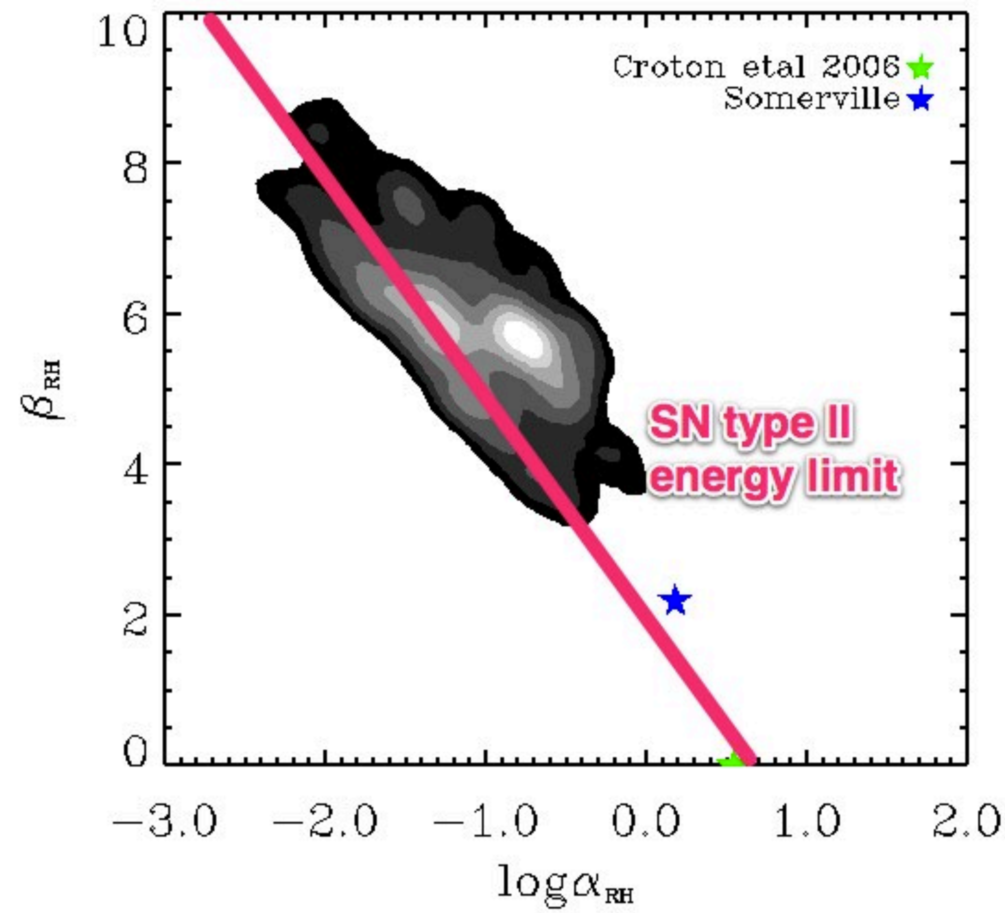
- 12 free parameters
- 1.5 million likelihood evaluations
- differential evolution markov chain using ~ 250 processors
- 13k cpu hours

slides from Yu Lu



slides from Yu Lu

- Although the model could match the constraining data, it fails to reproduce the evolution of SMFs.
- The model overuses energy that is available from SN type II; need to find other energy sources, model them, and test them.
- currently working on SAM comparison project with Lu, Somerville, Croton, Benson
- Galaxy formation far from solved... still way behind the data.



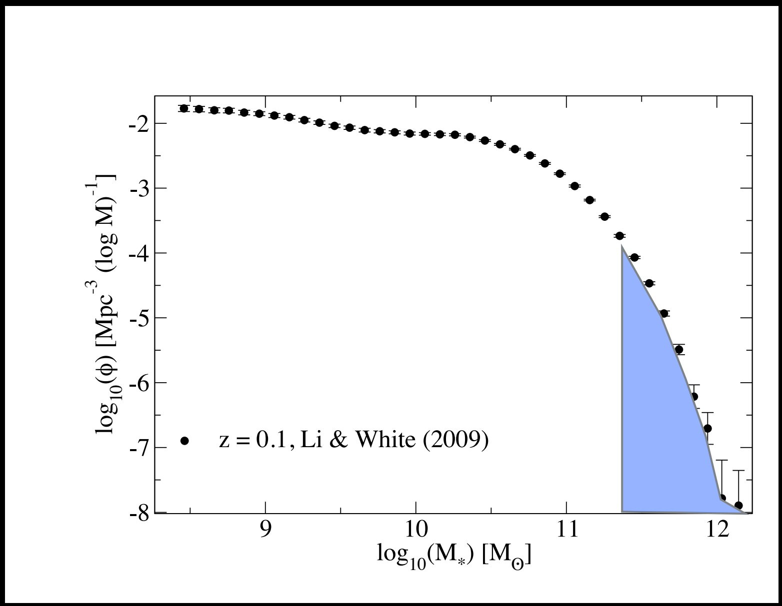
slides from Yu Lu

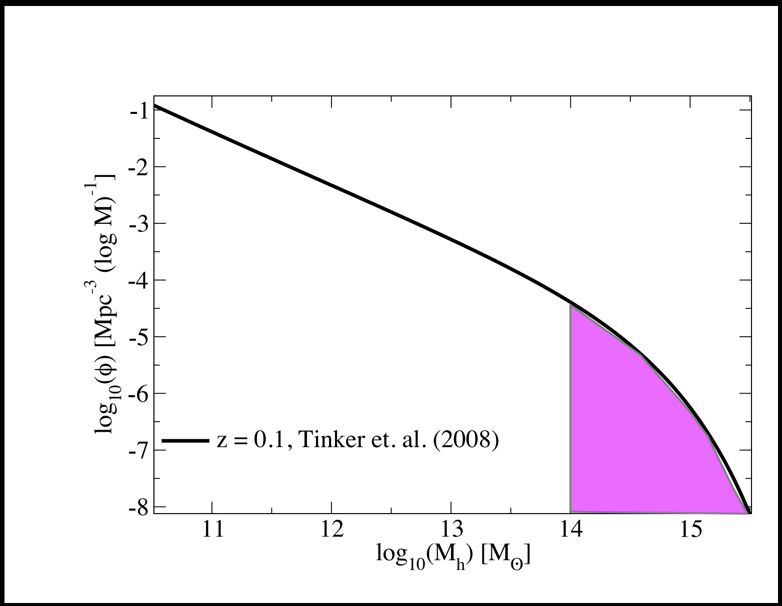
ways to model galaxies

- hydrodynamical simulations (resolve all histories, with baryonic physics)
- semi-analytic models (resolve all histories)
- empirical connection to dark matter
  - subhalo abundance matching (resolve all subhalos+histories)
  - halo occupation (resolve all host halos)
  - dark matter density based

resolution requirements depend on method.
correlations may depend on method.
what you can infer may depend on the method.

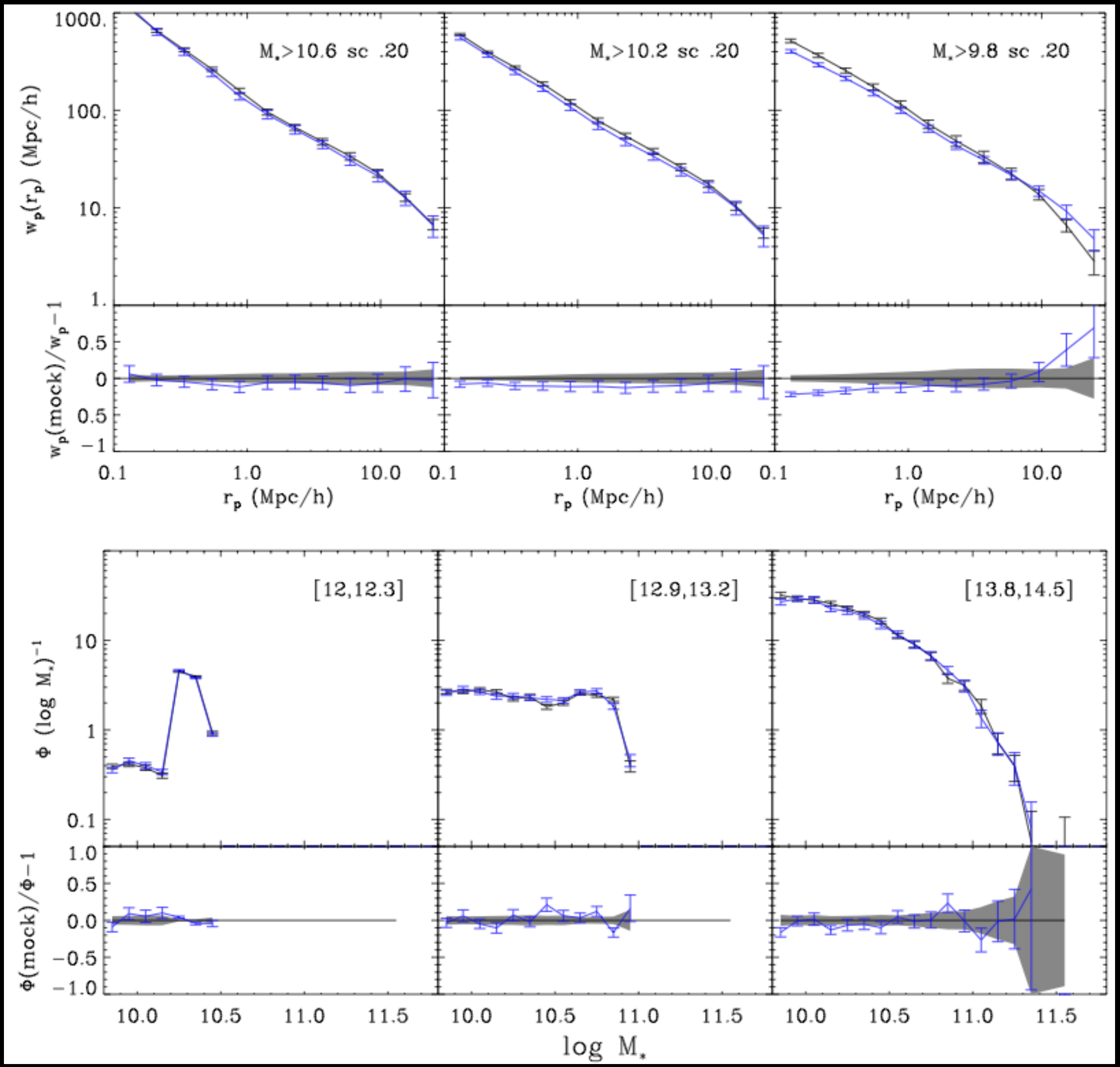
(sub)halo abundance matching





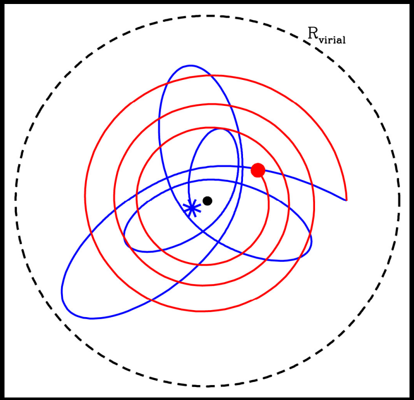
one galaxy per halo, including subhalos

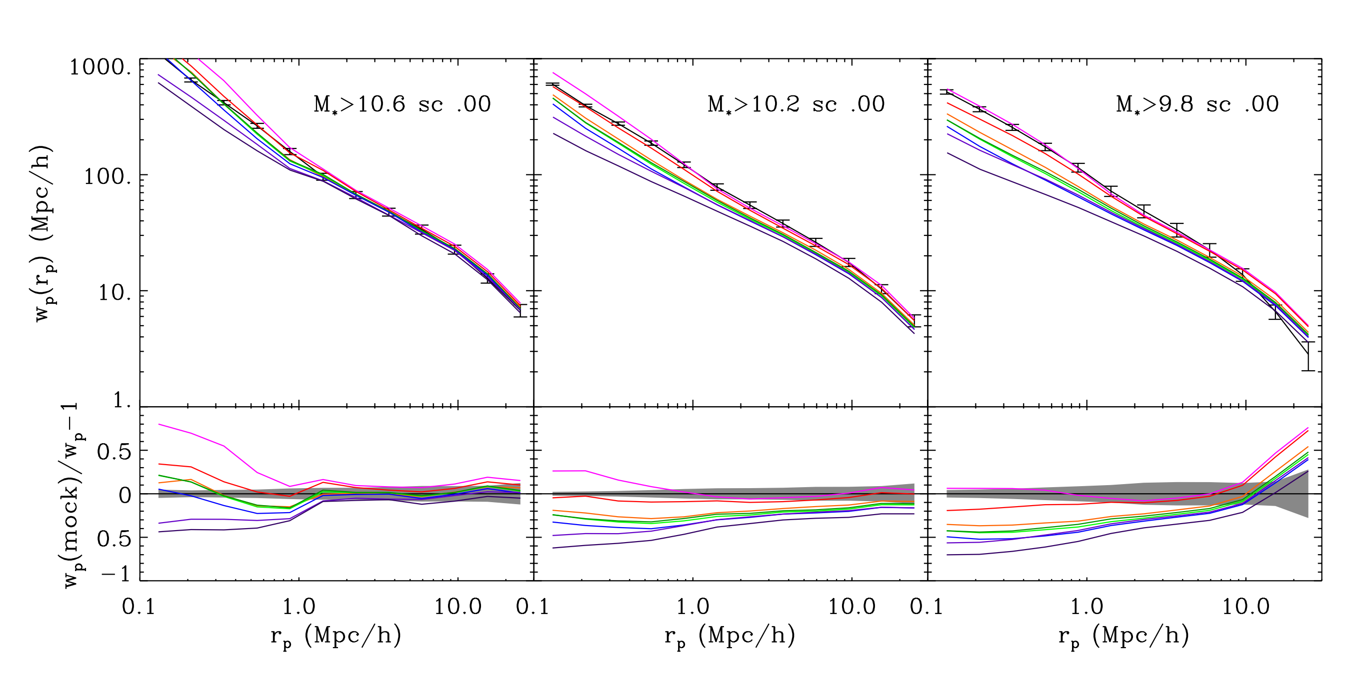
this works very well.

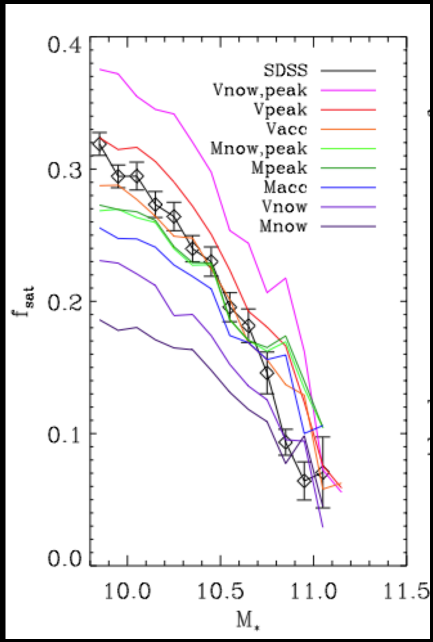


Reddick et al 2012

but details matter

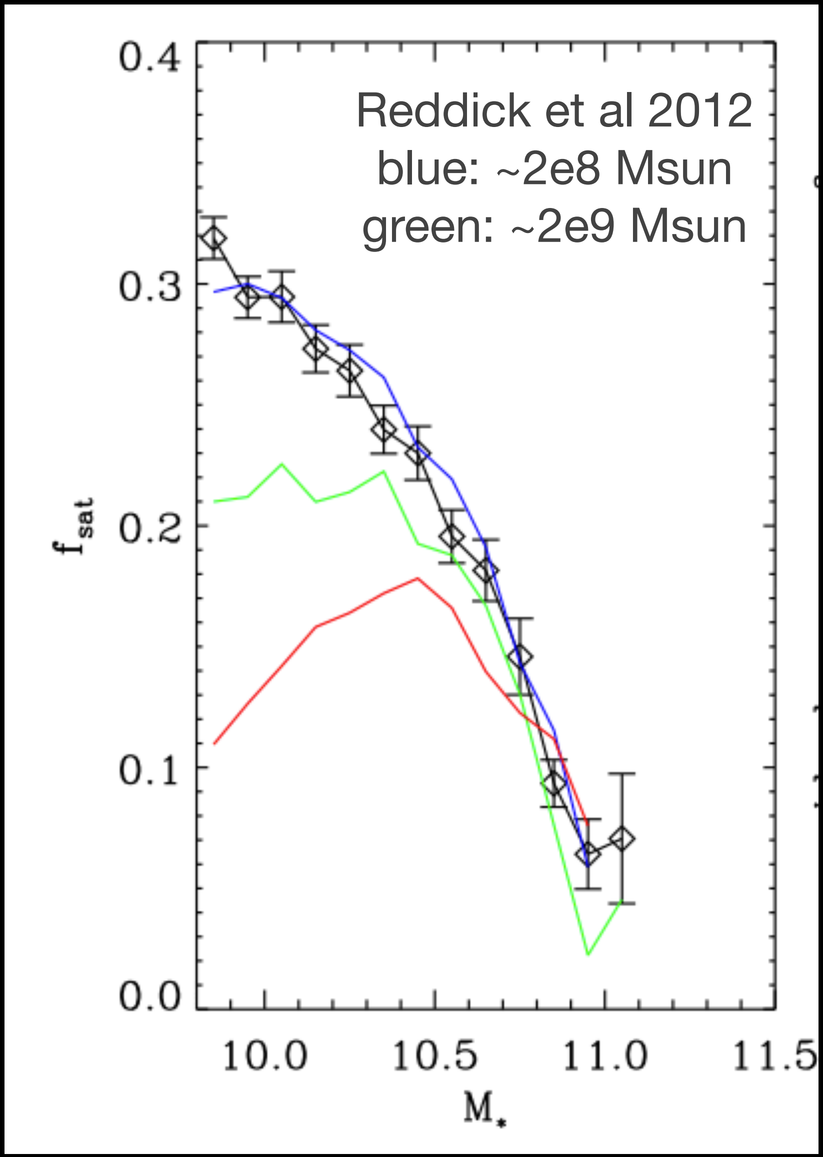




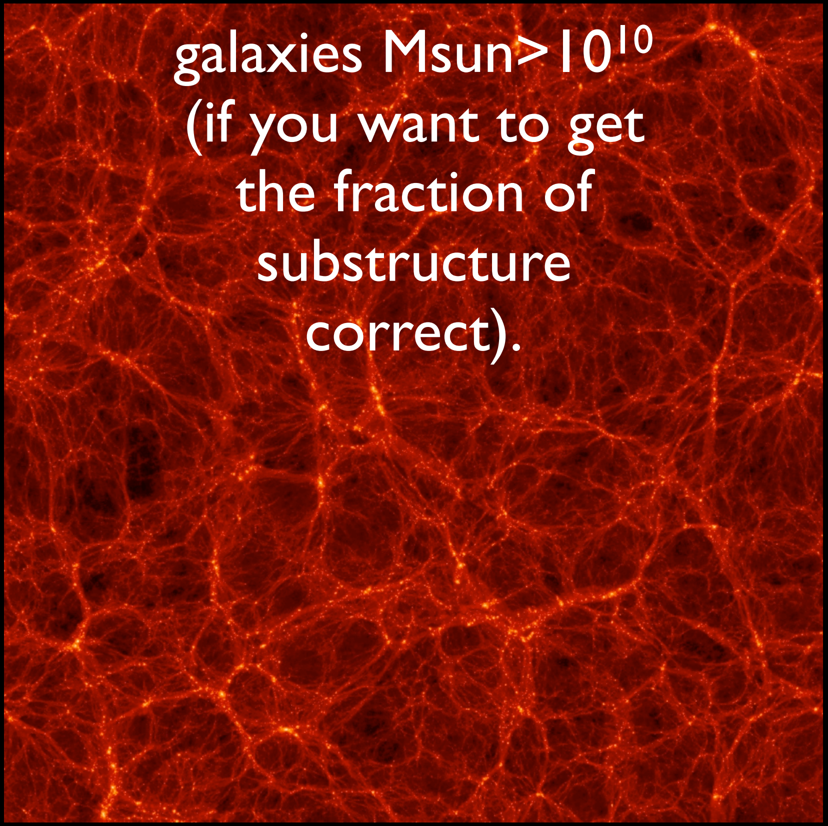


Reddick et al 2012

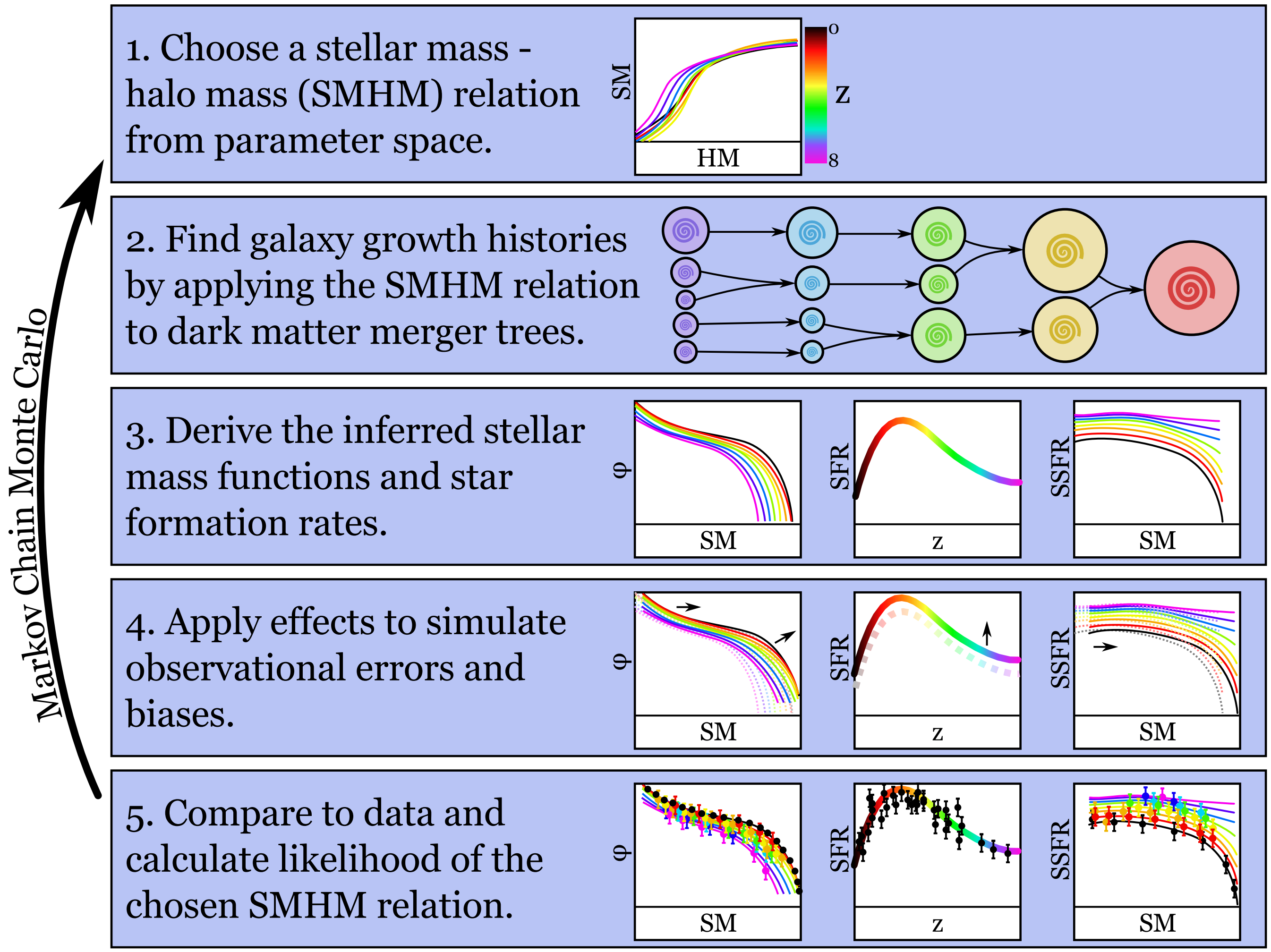
resolution requirements



357 Mpc,
1.9e8 Msun mass resolution
1.4kpc force resolution



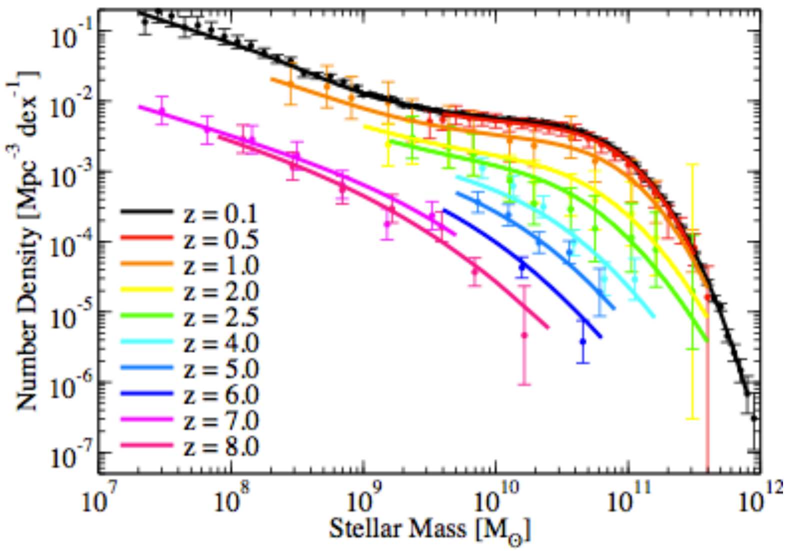
method: combine observations with halo statistics and growth

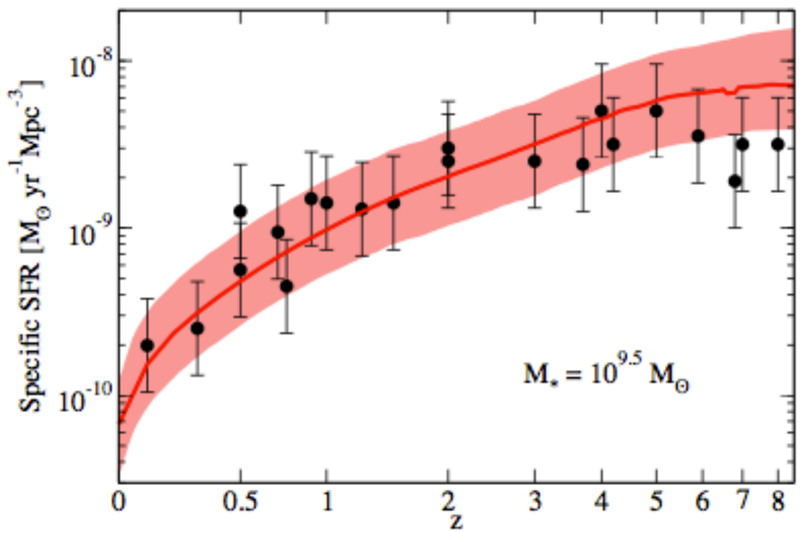


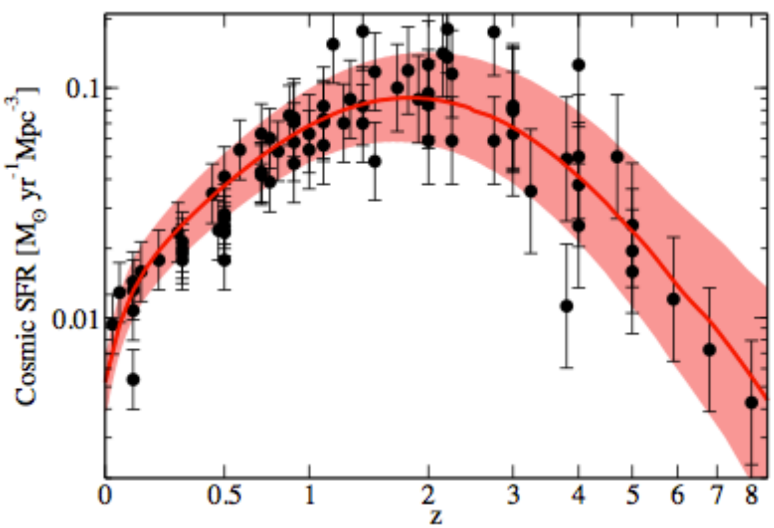
Behroozi, Wechsler & Conroy 2012 extension of approach in Conroy & Wechsler 2009, with better data, more realistic and detailed halo statistics, full accounting for errors and parameter degeneracies.

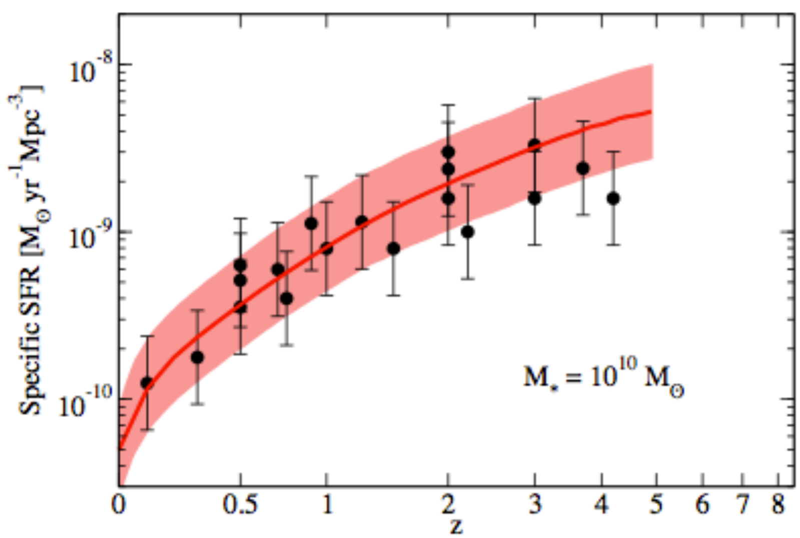
Results for best fit model

Behroozi, Wechsler & Conroy 2012







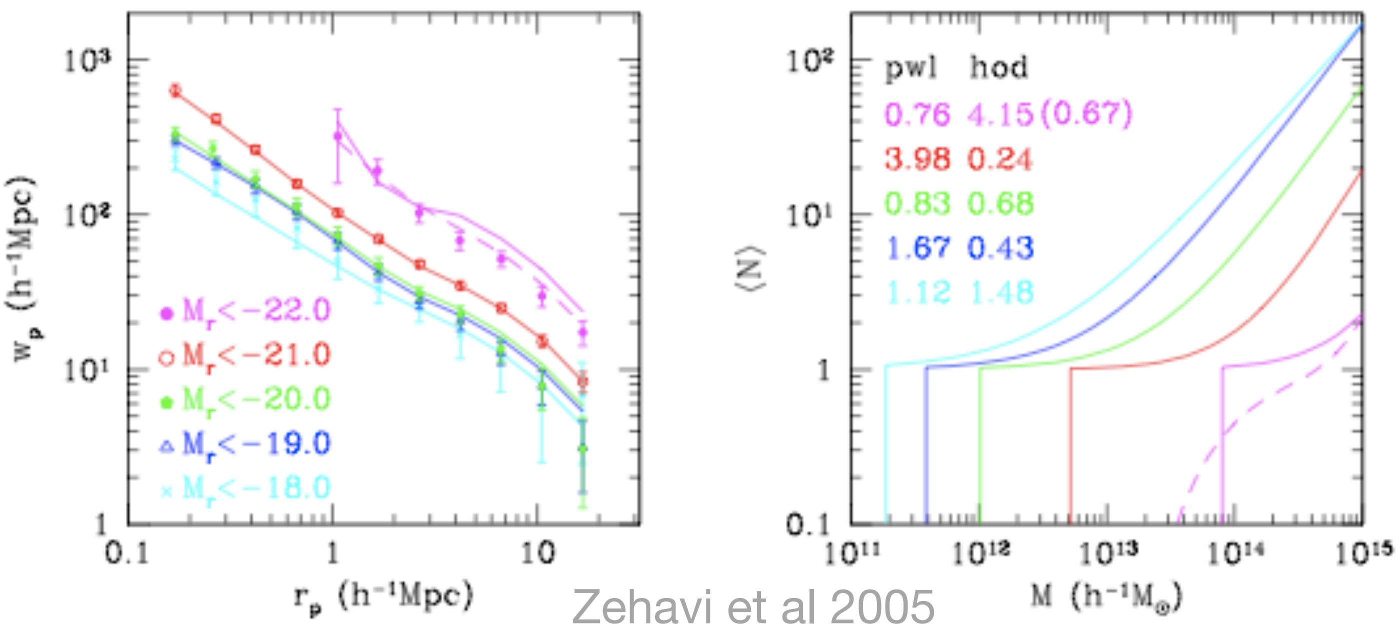


the halo occupation approach (HOD)

assume some form for the HOD, constrain it with clustering or other observables.

(eg. Scoccimarro et al 2002, Berlind & Weinberg 2002, Bullock, RW & Somerville 2002, Zehavi et al 2005, Tinker et al 2005, Zheng et al 2005, Tinker, RW & Zheng 09, Leauthaud et al 2012, + many many more)

generally, assume that galaxies have the same form of the HOD as subhalos, parameterized with ~ 3-5 parameters *per luminosity range*



Zehavi et al 2005

halo clustering and abundance + P(N|M) = galaxy clustering and abundance

conditional luminosity function

instead of parameterizing the number of galaxies with eg. L>L1 and L>L2 separately, parameterize the luminosity function as a function of mass

HOD: halo clustering and abundance + P(N|M) = galaxy clustering and abundance

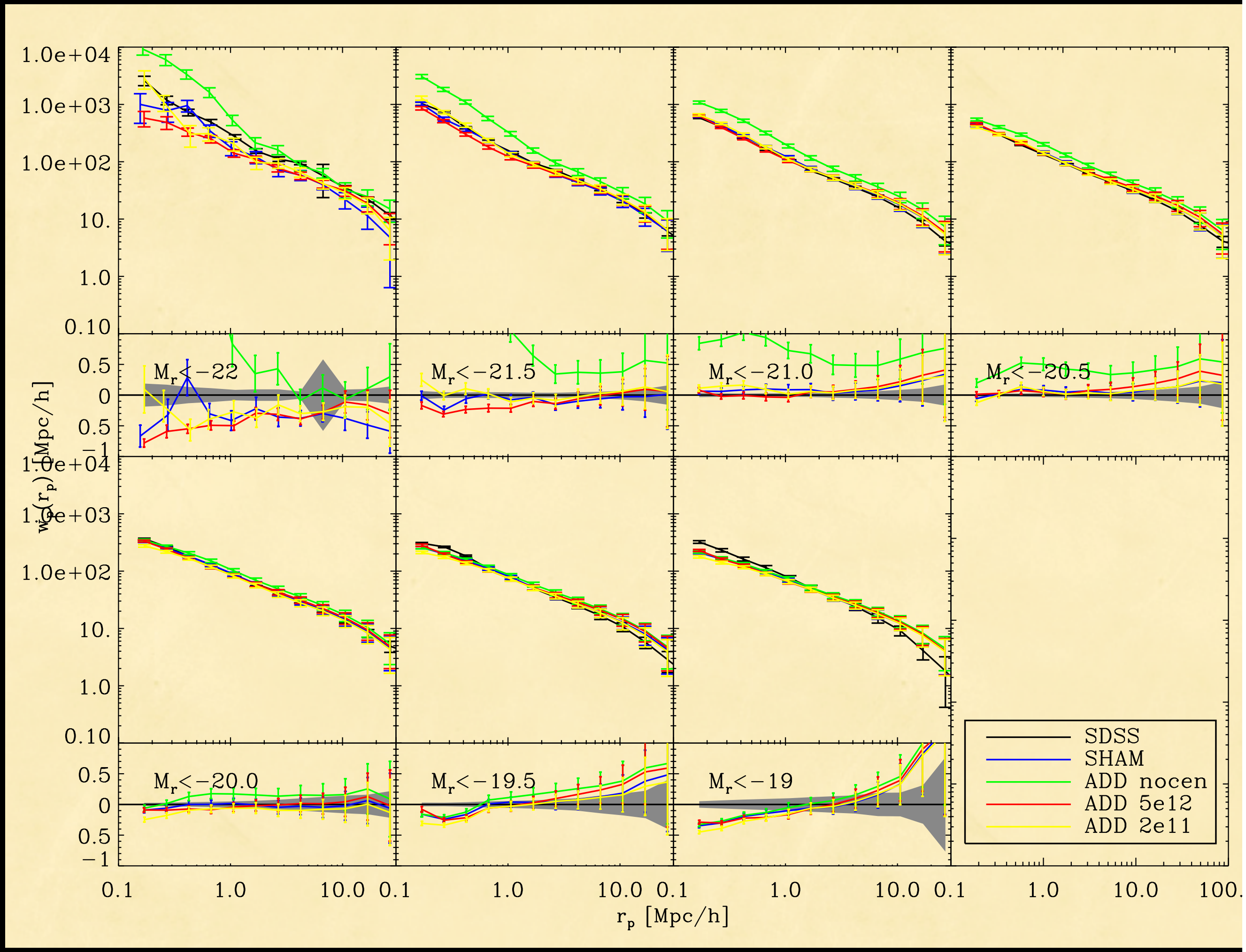
CLF: halo clustering and abundance + Phi(L|M) = galaxy clustering and galaxy luminosity function

advantage: model everything at once and get L
disadvantage: many free parameters; can be sensitive to functional form

(eg. Giavalisco & Dickenson 2001; Yang et al 2003; van den Bosch et al 2005; Cooray 2006; van den Bosch et al 2012; Lee et al 2009; DeBernadis & Cooray 2012)

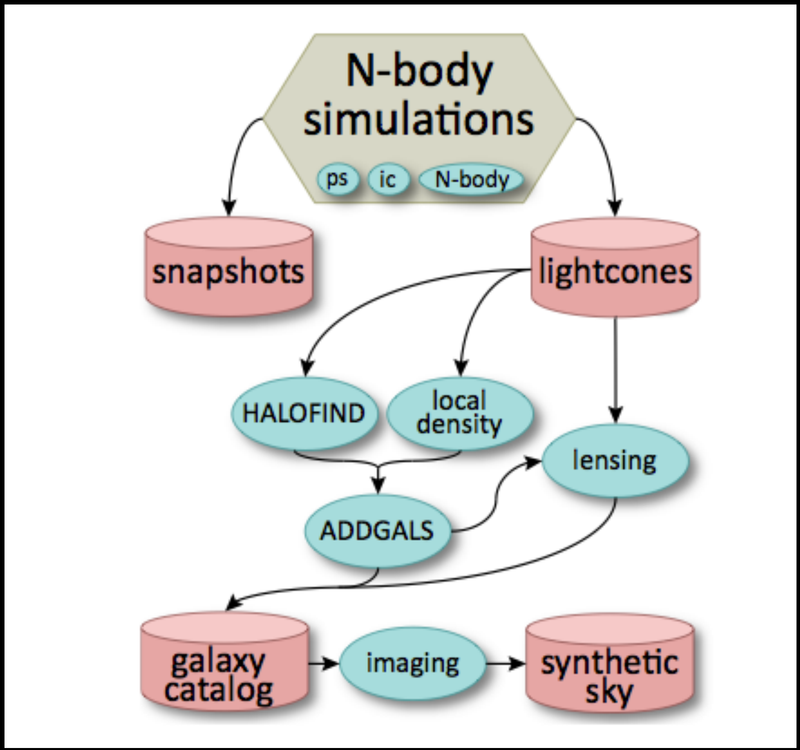
AddingDensityDetermined GAlaxies to Lightcone Simulations

- idea is to push resolution as far as possible, to simulate large volume surveys with minimal cost
- uses smoothed dark matter density to assign galaxies to particles with P(d|L)
- uses P(SED|L,dg) to assign colors



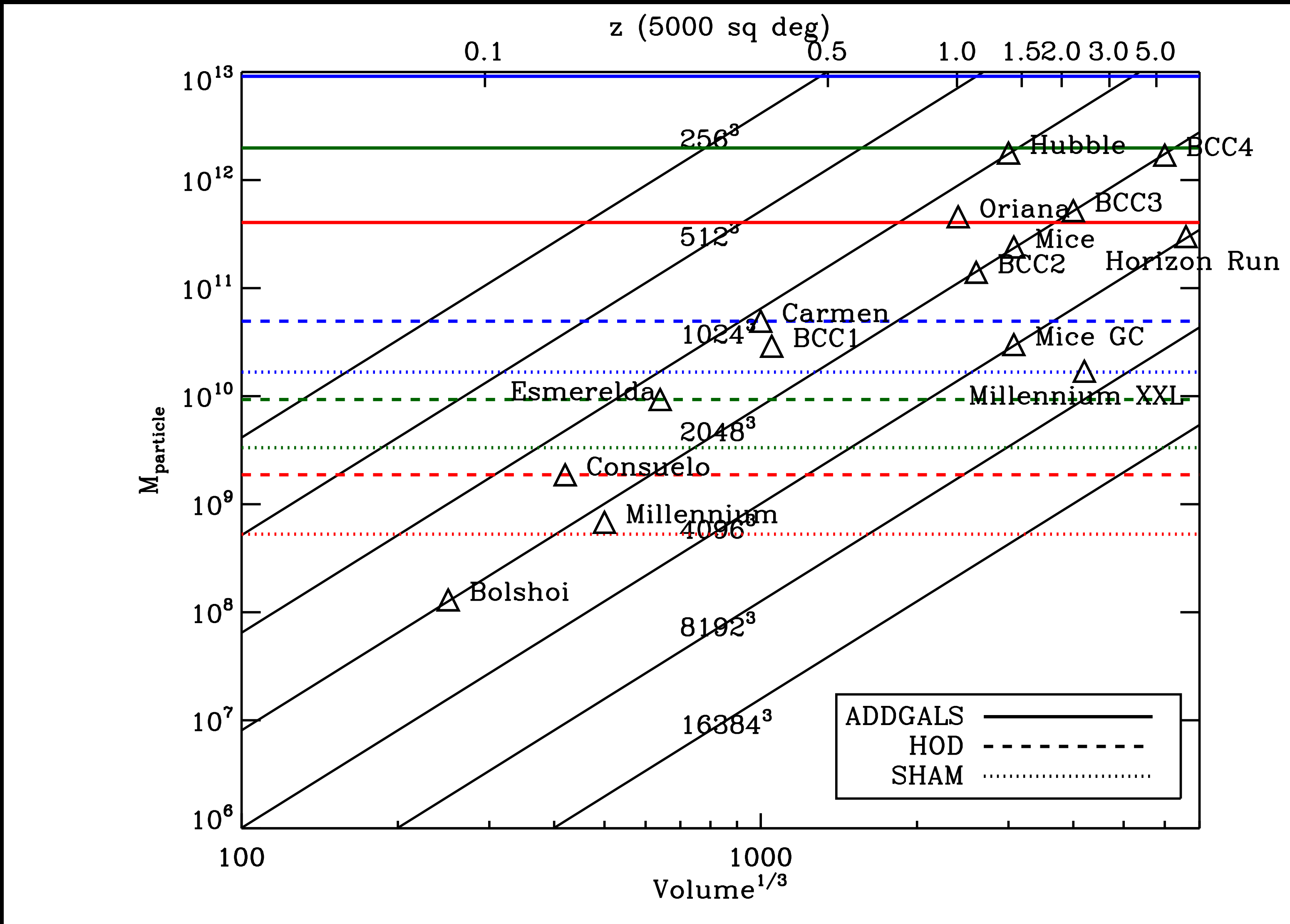
Wechsler, Busha, Reddick

synthetic sky pipeline



- full pipeline from ICs to a lensed, masked galaxy catalog
- full-sky lensing (shear & magnification) applied to all objects
- realistic colors, photometric error model
- extensive testing pipeline against current galaxy & cluster data
- have produced 10000 sq. degree lightcone to DES depth ~ 1 billion galaxies out to z ~ 2

Simulation needs for galaxy catalogs

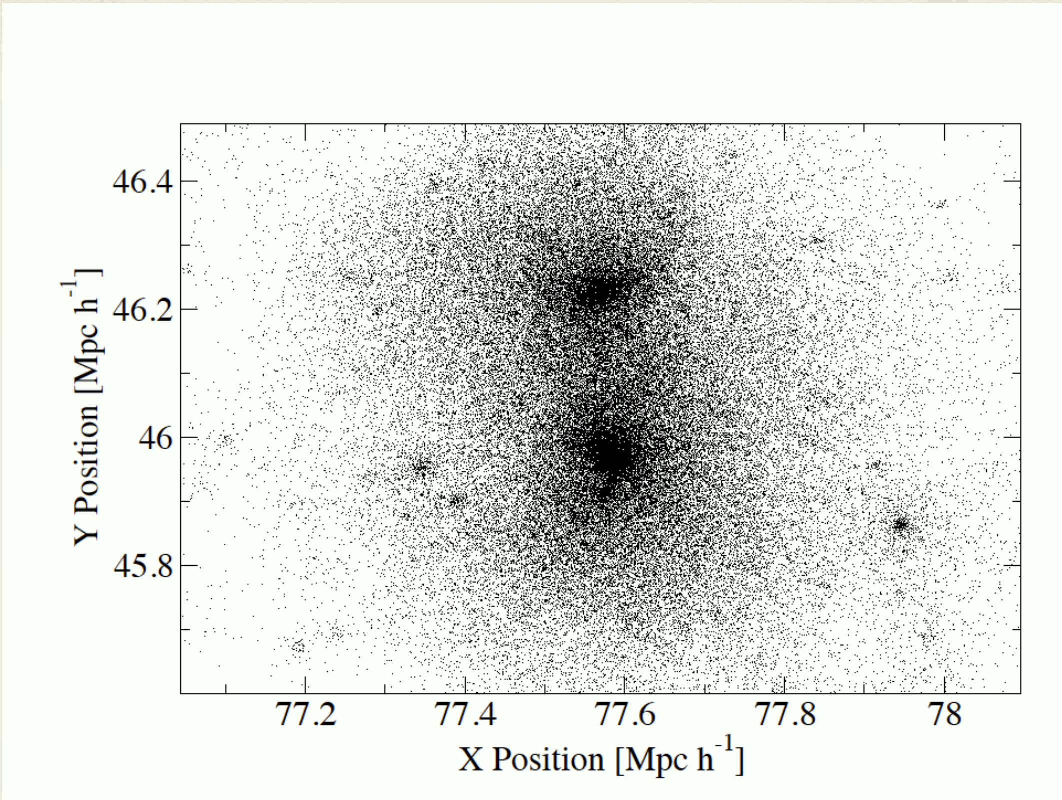


blue:-21
green:-20
red:-18

Busha & Wechsler

note: SHAM estimates too optimistic here.

Why Rockstar?



Phase-space halo finding = excels with halos in major mergers

Temporal information, too = great for merger trees

Why Rockstar?

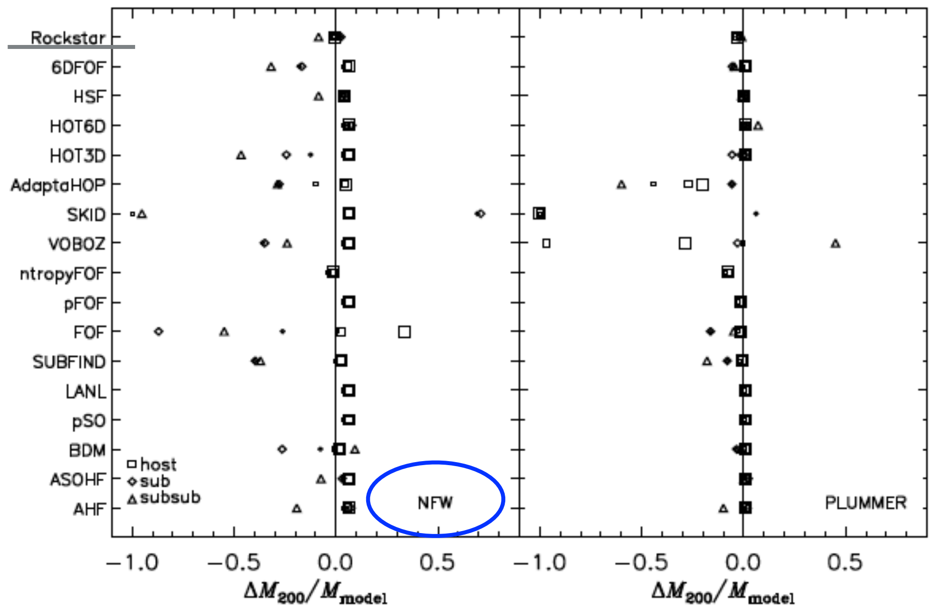


Figure 5. M_{200} mass (as determined from the supplied particle lists) measured according to the mean enclosed density being $200 \times \rho_{\rm crit}$ criterion for the NFW (left) and Plummer (right) density mock haloes extracted from each finder's list of gravitationally bound particles. The symbols have the same meaning as in Fig. 2

Knebe et al. 2011

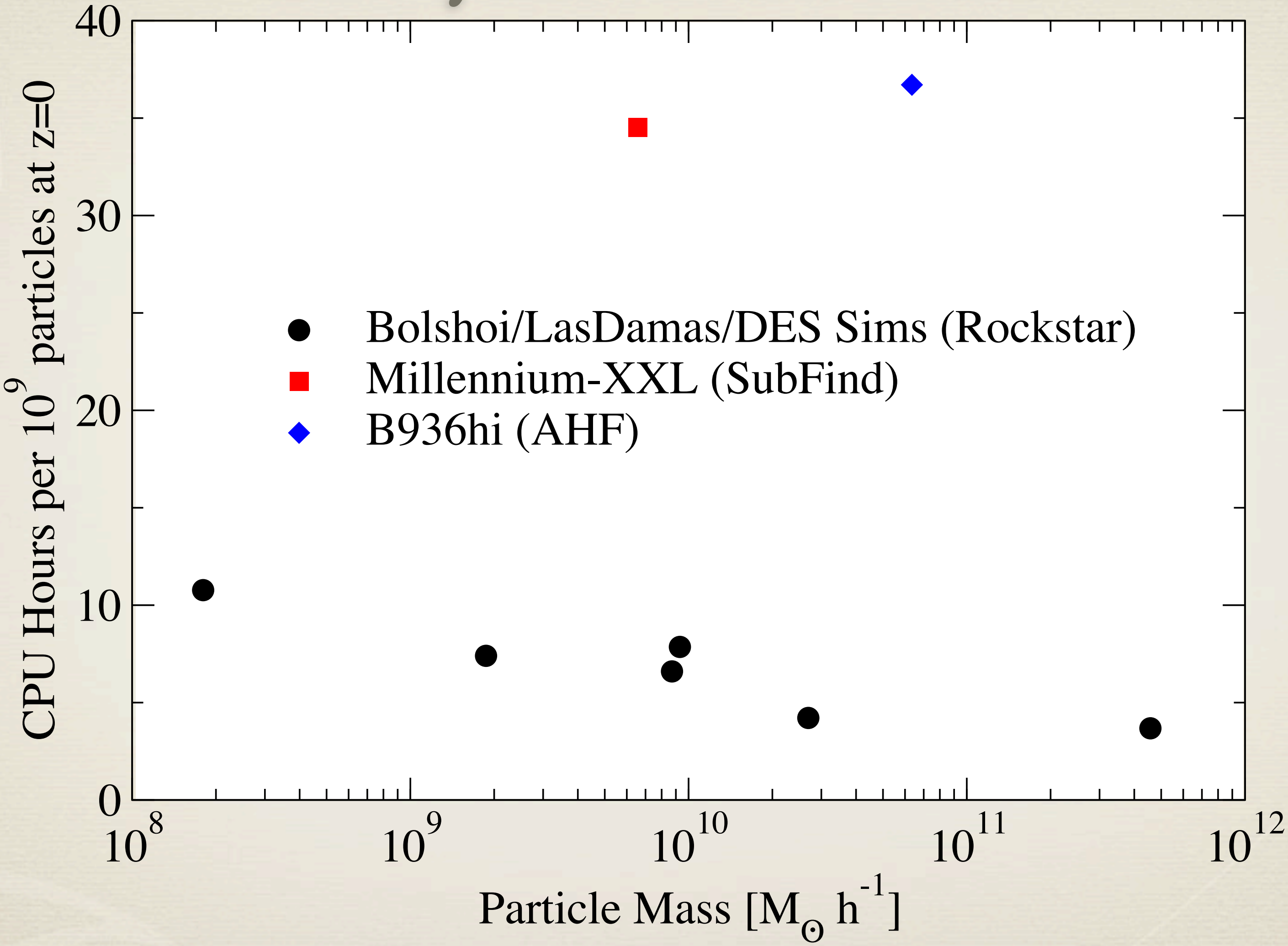
Accurate

Why Rockstar?

```c
#ifndef PARTICLE_H
#define PARTICLE_H

#include <stdint.h>

struct particle {
  int64_t id;
  float pos[6];
};

#endif /*PARTICLE_H*/
```

Memory Efficient (<60 bytes/particle total)

Why Rockstar?

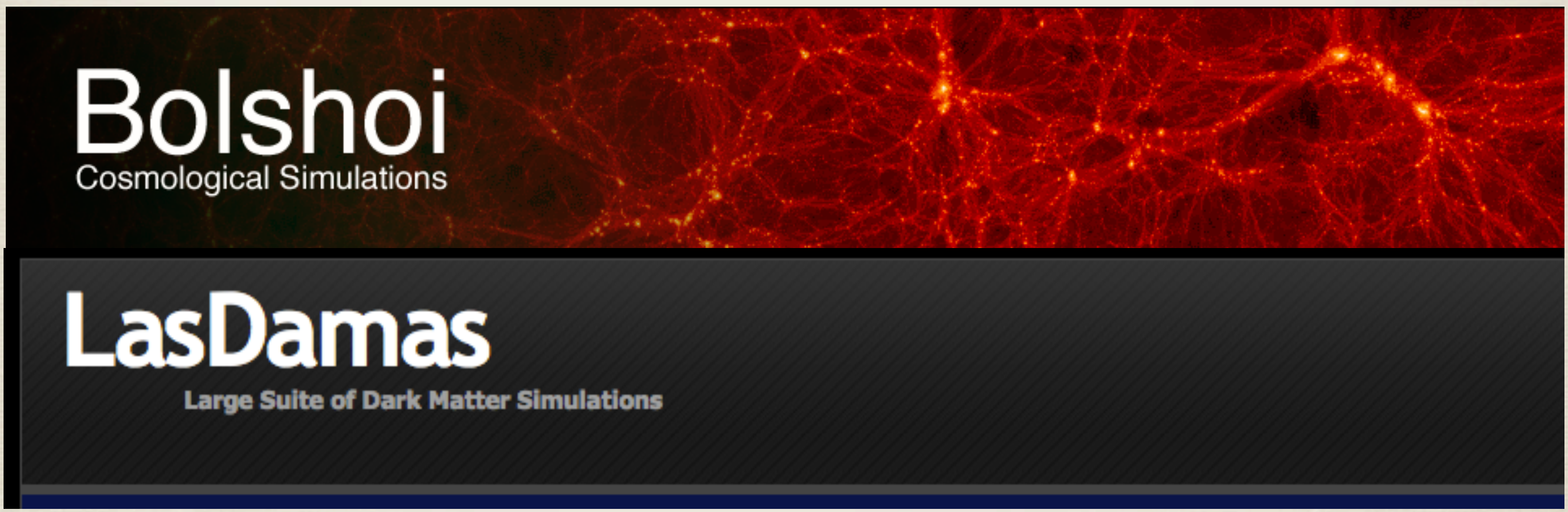


Extremely fast, can run on 1000's of processors.

Why Rockstar?

`http://code.google.com/p/rockstar`

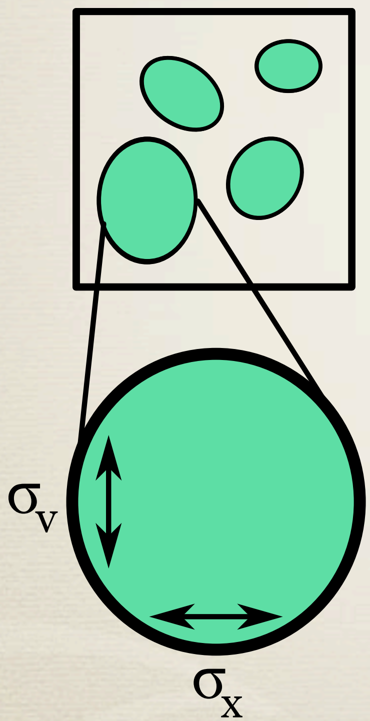
Freely available



Well-tested, already used by many major simulation projects.

How does it work?

Main idea:
Look for structure in velocity space as well as position space:



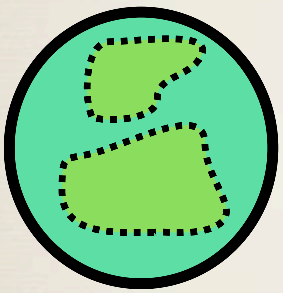
The simulation is divided into FOFs for easy parallelization.

For each group, particle positions and velocities are normalized by the group position and velocity dispersions, giving a natural phase-space metric.

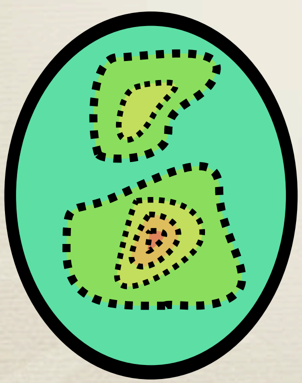
How does it work?

Main idea:

Look for structure in velocity space as well as position space:



A phase space linking length is chosen adaptively such that 70% of the group's particles are linked together.



Once all levels of substructure are found, seed halos are placed at the deepest substructure levels and particles are assigned hierarchically to the closest seed halo in phase space.

How does it work?

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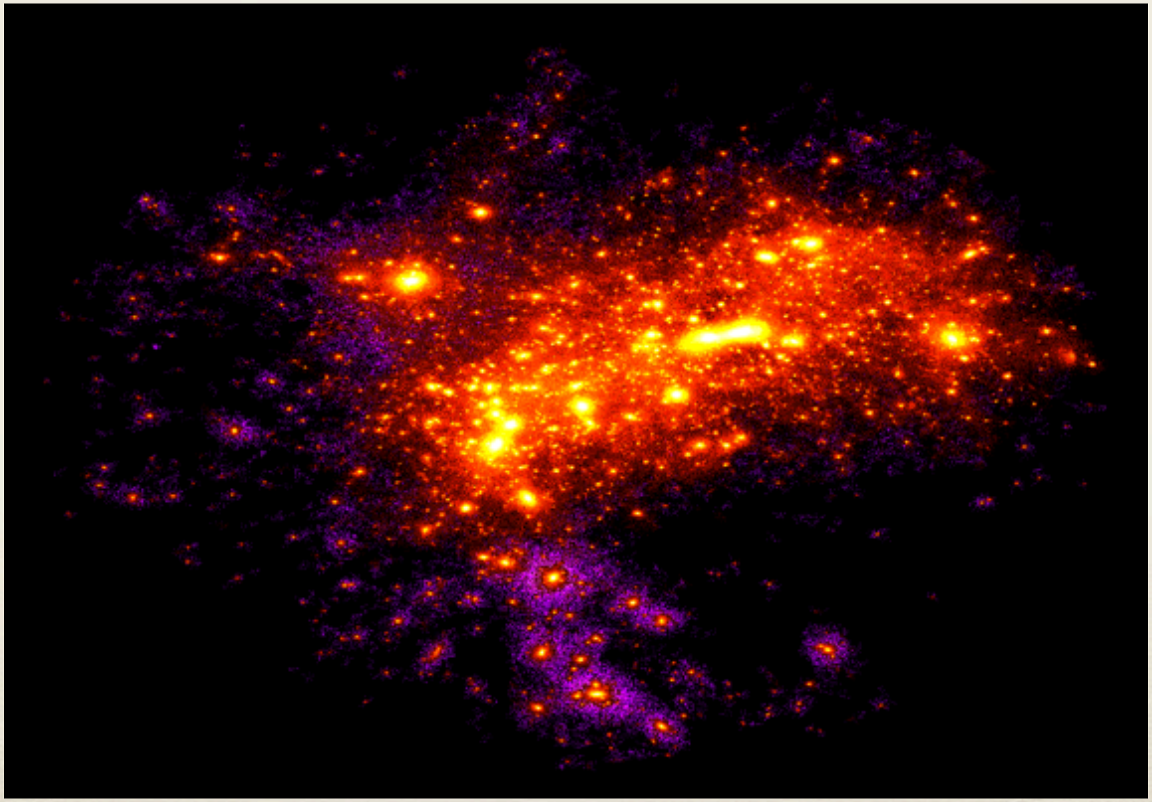
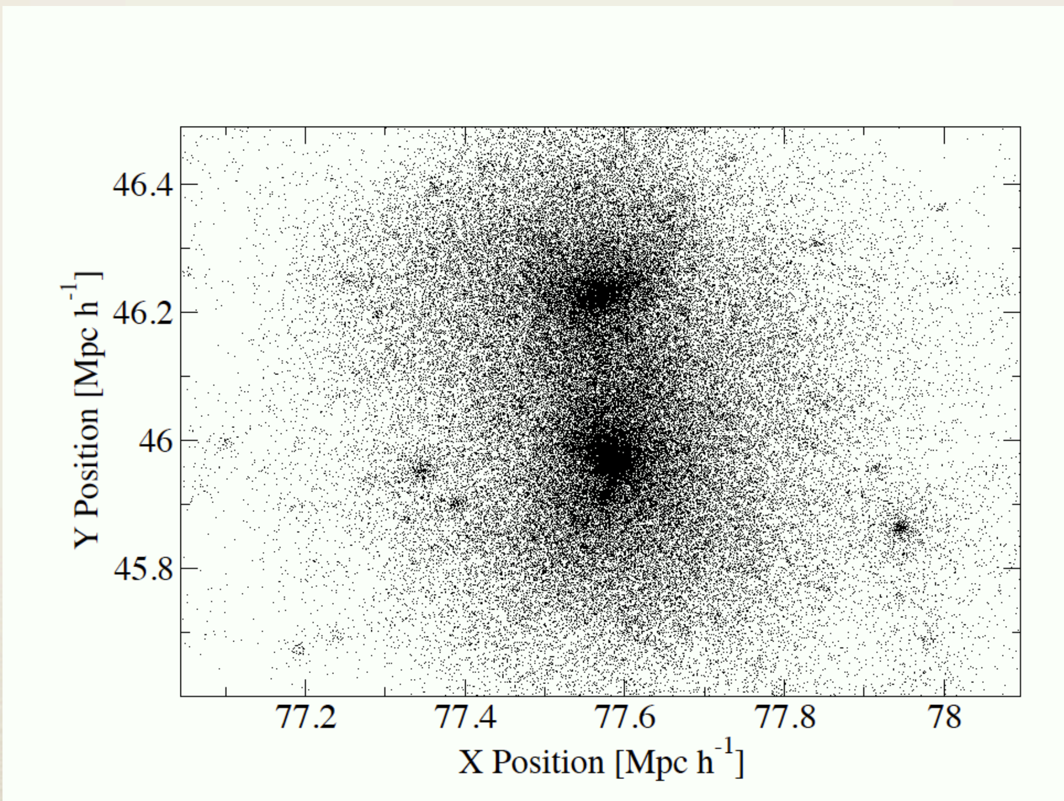
Look for structure in velocity space as well as position space:



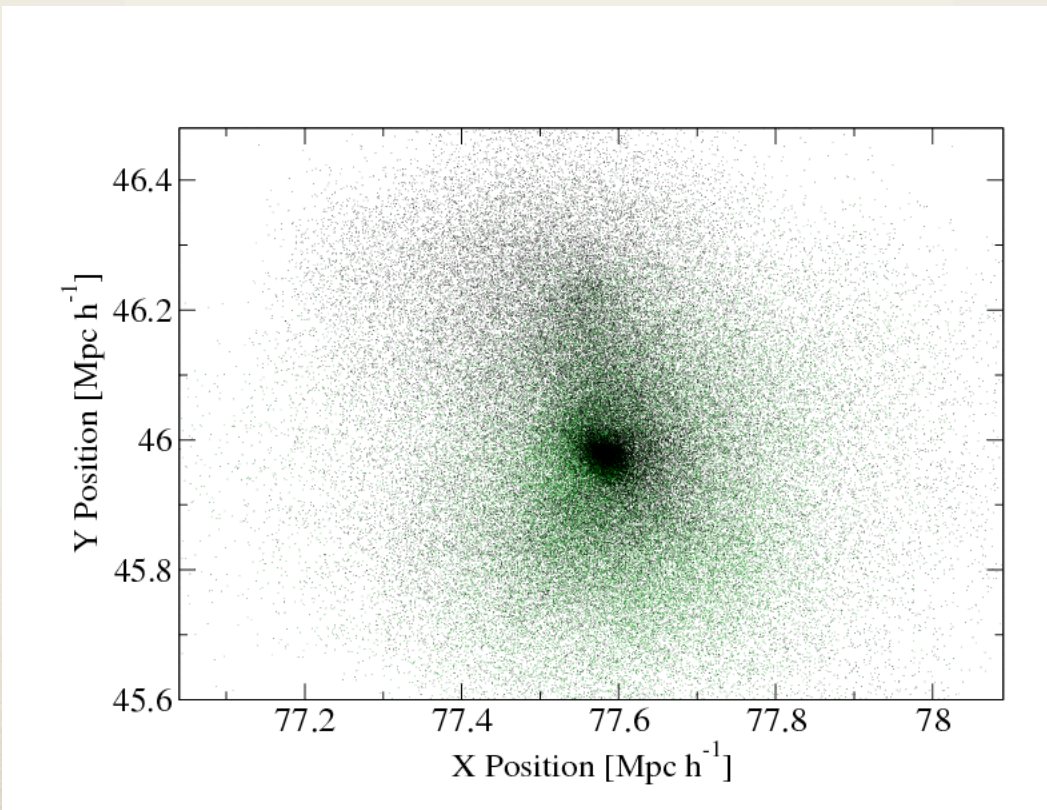
An Example

A major merger:



An Example

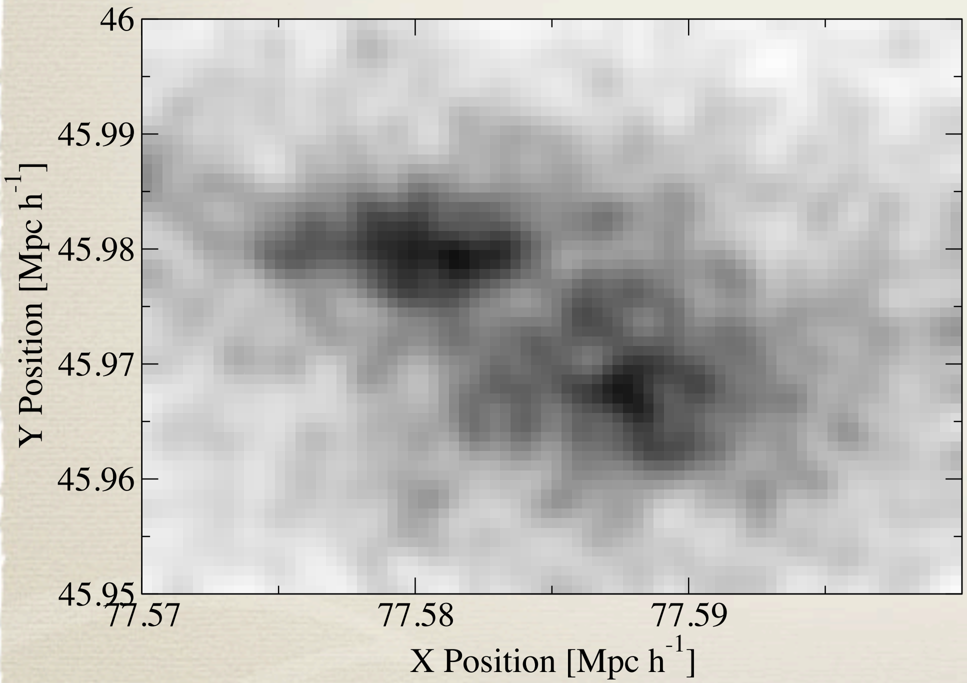
Host halo:



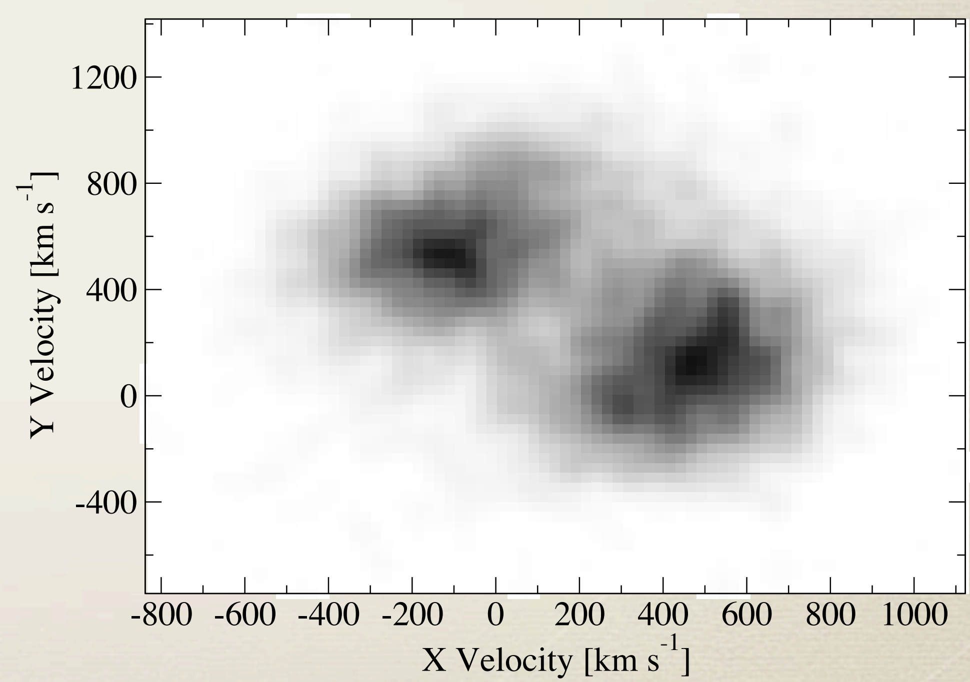
An Example

Actually, if you zoom in, host *halos*:

Position Space

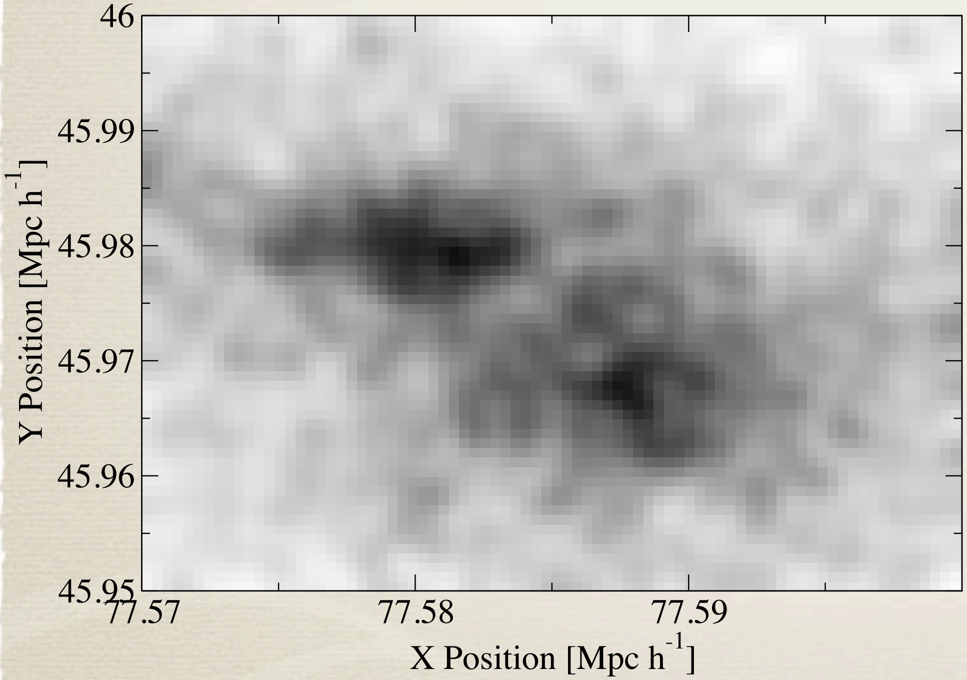


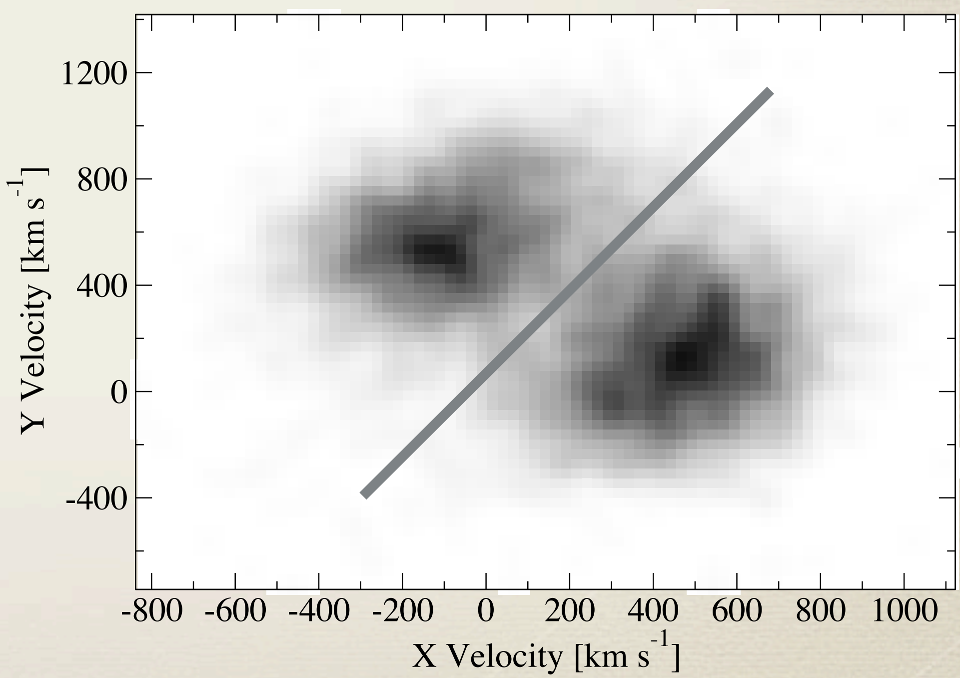
Velocity Space



An Example

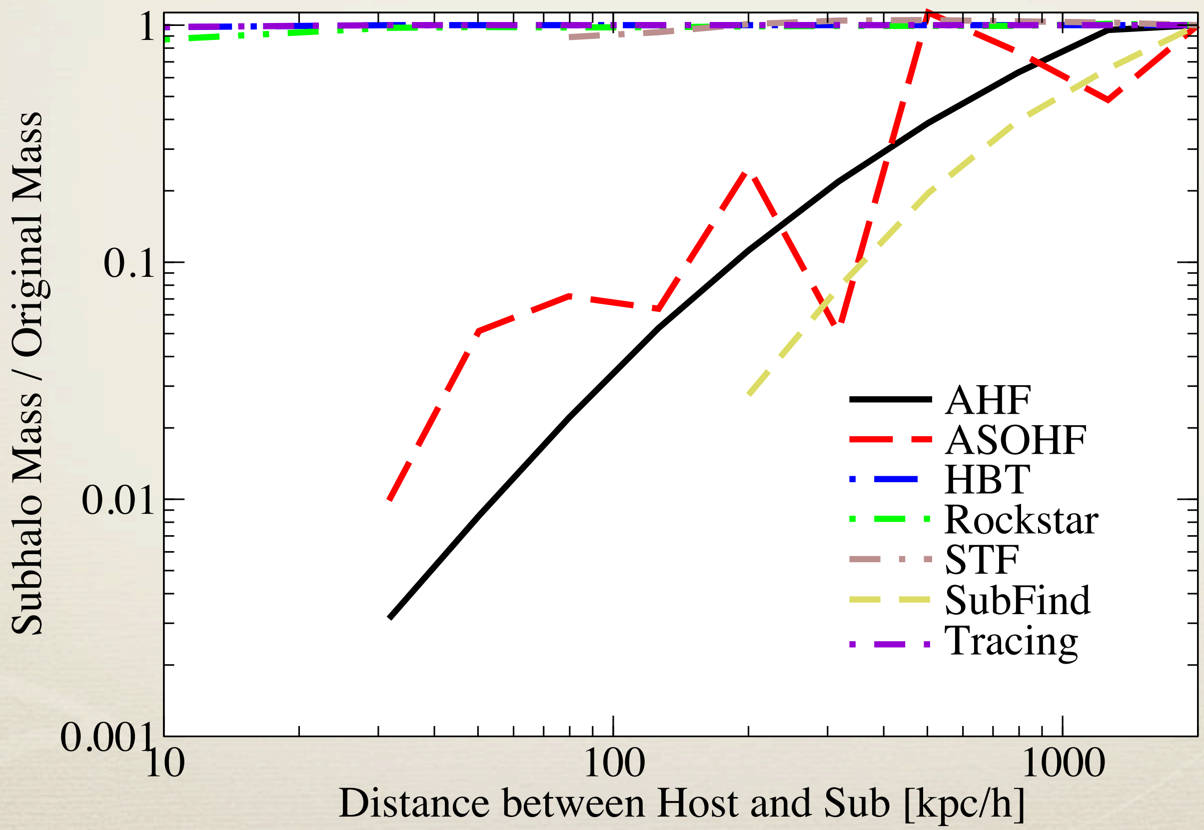
The extra velocity information helps enormously in separating particle membership:





An Example

Which translates directly into improvements in recovering massive halo mergers.



Merger Trees

What happens to galaxies in mergers?

How to tell that we've even tracked galaxies correctly?

Merger Trees

What happens to galaxies in mergers?

We can build explicit modeling of the gravitational evolution of halos into the merger tree code.

$$F = \frac{GM_1M_2}{r^2 + r_{vir}^2}$$

Gravitational Acceleration

$$\frac{dF}{dr} = \frac{2GM_1M_2}{r^3} > T_{min}$$

Tidal Merger Criterion

Merger Trees

What happens to galaxies in mergers?

We can build explicit modeling of the gravitational evolution of halos into the merger tree code.

We can then test explicitly for how well individual halo finders do.

Even better, we can interpolate between gaps in the merger tree and repair inconsistent links.